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THE OPTIMIZATION OF TOOL LIFE BY FILLET RADIUSON COLD FORGING DIE USING FINITE ELEMENT AND LOW CYCLE FATIGUE THEORY

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ABSTRACT

Tool life prediction is an important thing in the metal forging industry. To prolong die life, proper die design is crucial. The objective of this work is to study the fillet radius effect to tool life on taperd cold forging process. The predicted tool life of cold forging die with high stresses used low cycle fatigue (LCF) theorem with strain-life approach (e-N). The cyclic properties of die material as used an estimation formula model. Commercial FEM software (MSC Marc) was used to simulate the cyclic stress in atapered cold forging die with an elastic-plastic workpiece and a deformable die. An implicit non-linear 2D axisymmetric model with 4 node quadrilateral elements was used. The friction between the die and workpiece, obtained from ball-on-disc testing was 0.115. The die and workpiece materials were AISI D2 and AISI 1045, respectively. The various fillet radius of insert die were 0.8 to 1.5 mm. The reference model with fillet radius 0.8 mm was used to tool life comparison between prediction and experiment. From analysis, it was found the maximum stress was 5,717MPa and the minimum stress was 528MPa, and the crack initiation on the insert die by predictionbeganafter299 forging shots. From the experimental results, a 1 mm radial crack was found on the fillet of the insert die at 450 shots. From comparison between prediction and experiment, the different value was acceptable. Further more, the tool life prediction result from varying fillet radius that found the fillet radius as 1.5 mm gave highest die life of 7, 356 shots. The difference of die life between die fillet radius as 0.8 and 1.5 mm was about 24.6 times. From this work, the fillet radius was found significant to die life by the FEM and LCF prediction. However, the predicted tool life just establish a simple guideline for experimental works. Furthermore, experimental work to compare with predictions is still necessary.

KEYWORDS: Cold Forging Die, Fillet Radius, FEM, LCF, Tool Life Optimization & Stress Concentration

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Original Article

INTRODUCTION

Cold forging die is one of earliest metal working processes and has had a long history development. Today, forging still plays an important role in providing part and product. In cold forging, it is possible to use a lower cost steel grade since the strain hardening which occurs during forming, can improve both ultimate and fatigue strength. Thus forging is preferred in application where reliability, strength and economy are critical [1]. Die life depend on several factors, includes die material and hardness, work metal composition, forging temperature, condition of the work at the forging surface, type of equipment used, workpiece design and variety of other factors[2]. In cold forging process, where forging occurs at room temperature, leading to high die stress because of strain hardening of the workpiece lead to short tool life. The 4 main affected parameters on failure mechanism of die as including; 1) abrasive wear, 2) thermal fatigue, 3) mechanical fatigue and 4) plastic deformation [3]. The main factors of die failure are mechanical fatigue and deformation for cold forging and LCF regime, wear and temperature effect can

be eliminated. Mechanical fatigue failure of die is local damage, fatigue mechanism of metal material as including 3 stages as follow; 1) crack initiation, 2) crack propagation and 3) final fracture [4].

The fatigue failure mechanism when considered in microscopic can be described as follow: 1) crack initiation that is smallest crack, 2) short crack growth (crack size equal to grain size), 3) long crack growth (detect by eyes) and 4) final fracture. Fatigue crack mechanism of metal will occurred on discontinuity zone. Crack nucleation and grain size level we can denote crack initiation period, and long crack growth can denote by crack propagation period. In practice, it not easy to explicitly separate between crack initiation and crack propagation period. However, for metal material crack initiation period, crack length not larger than 2 times of grain size or approximately 1.0 mm [4]. The influent factors of metal fatigue as including; 1) sizing, 2) load type, notch or discontinuity zone and 4) surface finish. [4-5]. The 5 parameters effects of notches follow;1) concentrations of stress and of strain, 2) stress gradients, 3) mean stress effects and residual stresses, 4) local yielding and 5) development and growth of cracks.[6]. Fatigue life prediction method as a local strain approach and the notch or local stress-strain or load-notch strain relation can be determined by; experimental tests, analytical models and FEM techniques [6-8]. The 3 fundamentals of a local strain approach is as follows; 1) load-notch strain relations, 2) stress-strain laws and 3) damage and failure laws of material. Neuber[9] proposed among of these rule and Topper et al. [10] extended to metal fatigue problems. The local strain approach and the load-notch strain relations establish a local stress-strain history of a component subjected to arbitrary load history. For the local stress-strain, part server is a basic for damage and failure calculation [8]. Finite element method (FEM) birth and boom in 1960s. The application to metal forming problems as began as extension of structural analysis technique to the plastic deformation regime. Initial applications of the rigid-plastic finite element process were mainly in the analysis of compression and other simple process [11]. The Finite Element Method in Structural and Continuum Mechanics is the first FEM textbook was written by Zienkiewiczand Taylor since 1967s [12].

The advantages of using FE simulation in forging as reduced lead time reduced cost and technological improvement [13]. Many published papers in bulk forming both cold forging and hot forging with both 2D and 3D model as proposed by [13-19] just the name a few. The research papers that used fatigue theory for tool life prediction in cold forging, Falk et al. [15-16] and Lee and Chen [18] used fatigue theory predict tool life. Lee et al. [21] use Morrow’s equation based on stress-life (S-N) predicting tool life, the result found that Morrow’s equation model suitable to predicting tool life when compare to other model. Thara et al. [22] study to step reducing of cold forging socket head screw form 3 step to 2 step by using FEM simulation for determined cyclic stress on insert die and use Morrow’s equation to predict tool life the result found that tool life not difference cause to design process can be controlled of cyclic stress on insert die. For cold forging die simulation and material testing on LCF regime as done by [23-25] just the name a few. The results shown that the simulation agree to experiment.

The study of fillet radius of cold forging that affected to stress and die life, Petersen and Frederiksen [26]studied of fillet design in cold forging dies on a bolt-head die with 2D FEA as used. The main issue is to examine stress concentration and propagation of the plastic zone in the fillet area as applied forging pressure increases. Ab-Kadir et al. [27]was used of FE Deform for cold heading process with concerned fillet radius of die. It was found that when the fillet radius size was incresed, the heading process provided good precision and productivity due to intensification of the metal flow to infuse the die cavity. Abdullah et al.[28] To study for optimal design of cold forging die on closed forging of the universal joint. The Solid works program were carried out to modeling, stress and fatigue life analysis. The study focused

on the effects of corner radius of the die and part orientations to fatigue life of the die. From the result of studied, found that corner radius and part orientation gives significant effect to reduction of stress on the die and increase the service life of the die. From literature review as found the use of FEM and LCF theorem for cold forging die is widely use. However, the determination of die stress with parallel to forging simulation with deformable die still also limit.

The objective of this research is to study the effect of tool life due to varying fillet radius of die insert on cold forging die. The fillet radius of insert die were 0.8-1.5 mm. The cyclic material properties of die used estimation formula with universal slopes equation that proposed by Manson [29]. The low cycle fatigue (LCF) theorem was used for tool life predictions. FEM for forging process simulation on deformable die. The cold forging with included shrink fitting die insert. The tool life prediction from calculation will used to die design and testing under same condition. Cold forging experiments were conducted using AISI D2 as the die material and AISI 1045 as the workpiece material. The experimental work will be done for comparison crack initiation stage between predicting and testing.

THEORITICAL

Material Model

In the cold tapered forging simulation, the flow behaviour of workpiece material is elastic-plastic. The flow stress of workpiece is described in Equation 1.

$$\sigma = K\varepsilon^{n} \tag{1}$$

Whereσ is equivalent stress,ε is the equivalent plastic strain, K and n are material constants. The elastic deformation behaviour is employed for dies. For the insert die, the stress-strain state can be separated into 2 states: 1) the stress on the insert die from shrink fitting or pre-stress and 2) the cyclic stress from the forging process. The stress state varies from the contact area between the workpiece and insert die. In this research, the stress on die was fairly high due to a high reduction ratio and high billet material strength. The metal fatigue theory for predicting tool life with stress exceeding yield strength use was strain based (e-N) or LCF. The total strain life without mean stress can be expressed as in Equation 7.

$$\varepsilon_a = \frac{\sigma_f^{'}}{E}\left(2N_f\right)^{b} + \varepsilon_f^{'}\left(2N_f\right)^{c} \tag{2}$$

Where $\sigma_f^{'}$ is the fatigue strength coefficient, E is elastic modulus, $2N_f$ is the cyclic life and b is the fatigue strengthexponent. The values of $\sigma_f^{'}$ and b can obtain from material fatigue testing. $\varepsilon_p$is the plastic strain amplitude, $\varepsilon_f^{'}$is the fatigue ductility coefficient and c is the fatigue ductility exponent.

The cyclic properties of die material were obtained from the method of universal slopes equation estimation formula proposed by Manson [29]. The fatigue strength coefficient, fatigue ductility coefficient, ductility and tensile strength are described by (3)–(6), respectively.

$$\sigma_f^{'} = 1.9 \cdot R_m \tag{3}$$

$$\varepsilon_f^{'} = 0.76 \cdot D^{0.6} \tag{4}$$

$$D = ln\left(\frac{1}{1-RA}\right) \tag{5}$$

$$R_m = 4.02 \cdot HV - 374\ [MPa] \tag{6}$$

Where R_m is tensile strength, D is ductility, RA is reduction area and HV is Vickers hardness. From these equations, the fatigue strengthexponent b is -0.12 and the fatigue ductility exponent c is -0.6. From given, fatigue strength exponent b = -0.09 and fatigue ductility exponent (c) = -0.56. From AISI D2 with hardness 760 HV (60.5 HRC), ductility (D) is 1 [30] and reduction area (RA) is 1.5 [31]. The cyclic properties from estimation formula as 3411.75 and 0.104137 for fatigue strength coefficient and fatigue ductility coefficient, respectively.

GEOMETRY AND FE MODEL

The tapered part on this work was a 1 step forging or perform process. The initial billet size was Ø19x20 mm, the die insert size was Ø36x45 mm and the die ring size was Ø100x45 mm, as shown in Figure 1. The FE model, workpiece was axisymmetric; the use of 2D axisymmetric quadrilateral 4 node element meshes and used a finest element mesh on fillet radius for higher result accuracy.

The analysis was implicit non-linear contact with a 0.115 friction efficiency. The global edge length element of die ring, die insert and billet were 1, 1 and 0.4 mm, respectively. The smallest element size on the die fillet radius and meshes of the workpiece was 0.025 mm. An elastic-plastic with adaptive meshes followed a power law for the workpiece and a deformable die with elasticity was used. The shrink fitting between die ring and die insert was 0.075 mm. The detail of the FE forging process is shown in Figure 2.

An elastic-plastic flow stress-strain followed a power law for the workpiece was obtained from tensile testing of AISI 1045 follow JIS-Z1993-2241: Tensile test standard. The engineering stress-strain and true stress-strain flow curve from tensile testing as shown in Figure 3. The material properties of dies and workpiece for forging process simulation are shown in Table 1. The reduction ratio is 0.92 that exceeded to principle strain allowance of material as 0.8 [32].

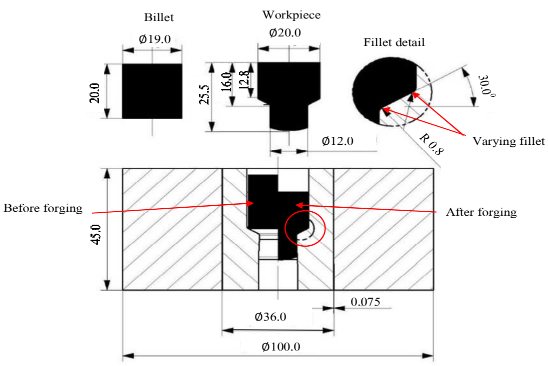

Figure 1: Die and Workpiece Dimension

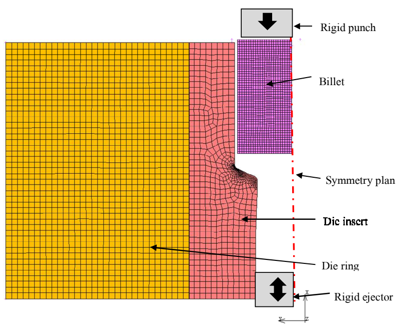

Figure 2: 2D FE Axisymmetric of Forging Process

Table 1: Mechanical Properties of Die and Workpiece [21,29]

Description	Material	Elastic Modulus [GPa]	Poisson's Ratio	Yield Stress [MPa]	Strength Coefficient [MPa]	Strain Hardening Exponent
Workpieces	AISI 1045	207	0.29	462.6	1,288	0.22
Die	AISI D2	209	0.3	1,874.3	-	-

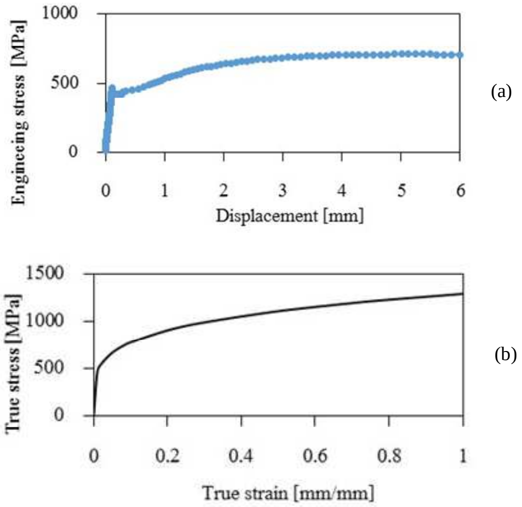

Figure 3: Flow Stress-Strain Curve of Workpiece (a) Engineering Stress-Strain and (b) True STRESS-Strain

METHODOLOGY

For compare to FE simulations, The tool life prediction from calculation will used to die design and testing under same condition. Cold forging experiments were conducted using AISI D2 as the die material and AISI 1045 as the workpiece material. The fillet radius of insert die for experimental work was 0.8 mm that is lowest radius on this study. The experimental work will be done for comparison crack initiation stage between predicting and testing. The various fillet radius of insert die on FE model are follow; 0.8, 1.0, 1.2 and 1.5 mm. The detail of the die set in forging process is shown in Figure 4.

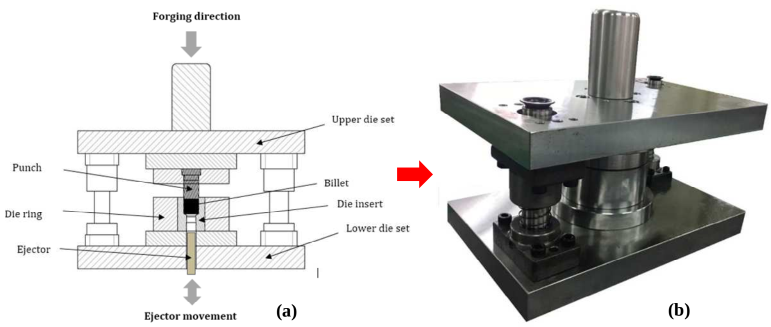

Figure 4: Die Set Assemble (a) CAD Model and (b) Completed Die Set

RESULTS AND DISCUSSIONS

From the FE forging die process simulation, the die insert model with fillet radius 0.8 mm found the minimum stress was 528MPa from initial contact forging step and the maximum stress was 5,717MPa from forging at the final step.

The highest or peak stress occurred on the upper fillet radius of the insert die, as shown in Figure5. From the cyclic stress of the insert die, the of the insert die from LCF fatigue theorem can be calculated follow Equation (2) the crack initiation of insert die as 299 shots. From the experimental results, a 1 mm radial crack was found on the lower fillet of the insert die at 450 shots as shown in Figure 6.

The experimental results showed that the die life was significantly greater than predicted by the FEM. The crack initiation point from experiment similar to FE simulation that occured on fillet radius that highest stress due to stress discontinuty or notched stress concentration [6-10]. For the billet and workpiece from forging as shown in Figure 7. whrere (a) comparison between billet to workpiece and (b) comparison of workpiece to design dimension, the result shown that dimension coincident between design to actual part. However, the initiation crack was occurred on die insert not affected to workpiece due very small crack size.

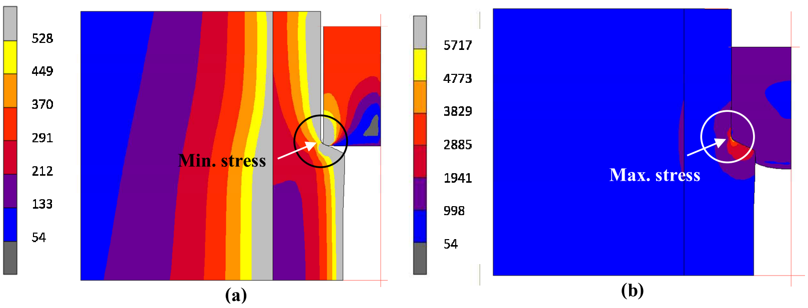

Figure 5: Stress Result on Insert Die (a) Minimum Stress and (b) Maximum Stress

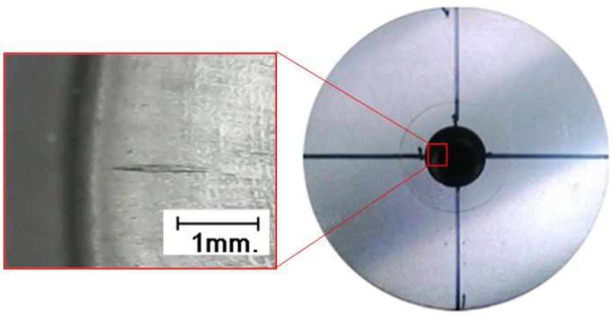

Figure 6: Crack Initiation on Insert Die

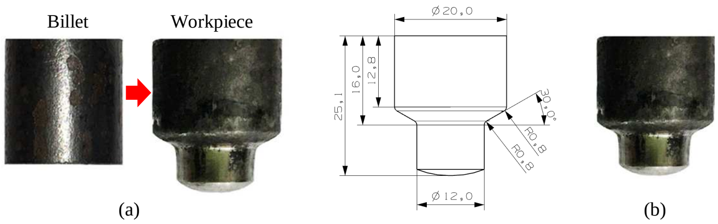

Figure 7: Tapered Workpiece from Forging (a) Billet and Workpiece and (b) Dimension Drawing and Workpiece

To comparison of die insert crack initiation between calculation to experimental works, tool life from prediction as 299 shots and tool life from experimental works as 450 shots. The difference from prediction with experiment is about 155 shots that is acceptable value. In practically, to detecting 1 mm crack size on cold forging die is not easy. The end of the crack initiation stage of steel is a couple of grains of the material and crack size range from about 0.1 to 1.0 mm [4]. The FEA result of cyclic stress, cyclic train and tool life prediction from varying of fillet radius of die insert as shown in

Table 2. The minimum stress and strain of die insert from initial contact from all model are small difference but the maximum stress and strain from final step large differencs. The die with larger fillet radius gave lower maximum stress that directly affeted to stress range. The highest and lowest stress rang are 5,189 and 3,234M Pafrom die fillet radius is 0.8 and 1.5, respectively.

Table 2: Tool Life Prediction of Various Fillet Radius on Insert Die

Fillet Radius [mm]	Min. Stress [MPa]	Max. Stress [MPa]	Min. Strain [-]	Max. Strain [-]	Strain Range [MPa]	Stress Range [-]	Tool Life [Shot]
0.8	528	5,717	0.0025	0.0274	0.02483	5,189	299
1.0	537	4,715	0.0026	0.0226	0.01999	4,179	625
1.2	511	4,331	0.0024	0.0207	0.01828	3,820	2,173
1.5	532	3,766	0.0025	0.0180	0.01548	3,234	7,356

The tool life result from predicing by FEM and LCF theory as shown in Figure 8. The lowest tool life was 299 shots, with die fillet radius as 0.8 mm. The highest die life was about 7,356 shots, with die fillet radius as 1.5 mm. The difference of die life between die fillet radius as 0.8 and 1.5 mm is about 24.6 times. The fillet radius showed that was significantly to die life by the FEM, the die life proposional to fillet radius size.

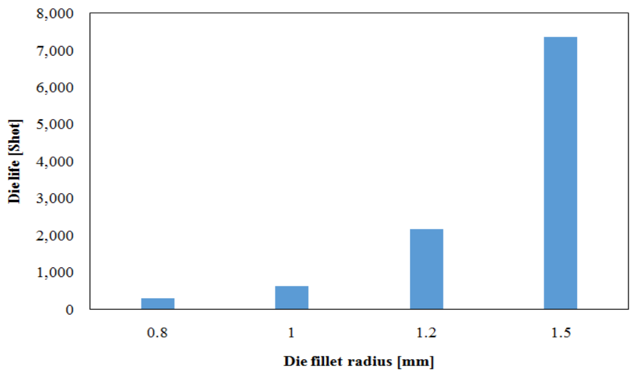

Figure 8: Life of Insert Die with Various Fillets Radius

In this work, even though to clearify that increasing fillet radius of insert die can help to prolong die life. However, the experimental works for compared to several fillet radius still also need. The comparison of tool life with varying fillet radius cold tapered forging on this works is just a guideline for prolong die life by stress concentration reducing. However, each part or die design will have a fillet radius limit. The many way to improve tool life such as die material treatment or changing, tapered angle of die or shrink fitting ratio ware most interesting for further study.

CONCLUSIONS

The study of tool life optimization on insert die by fillet radius by used of FEM for cold forging process simulation and LCF for tool life prediction in low cycle regime can be drawn as follow:

- The forging process simulation using FEM can help determined to minimum and maximum of stress-strain on fillet radius of die insert cold forging die. While the analytical models still also limit for calculating to complex shape model with shrink fitting.
- Circumferential crack initiation occurred on fillet radius of insert die from experimental works agreed to FEM analysis result. The cracked point was the highest stress range on insert die.

- The used of universal slope estimation fomula material cyclic properties of die for tool life prediction in LCF regime is acceptable. The tool life comparison between predicting to experimental work are reasonable.
- Larger fillet radius can be reduced maximum stress by reduced stress concentration on fillet radius. In this work, die life depending to fillet radius, higher fillet radius gave higher die life.

Even though to clearify that increasing fillet radius of insert die can help to prolong die life. However, the experimental works for compared to several fillet radius still also need. The work just a guideline for die designer to simply prolong die life by reduced the stress concentration. However, each part or die design will have a fillet radius limit. The many way to improve tool life such as die material treatment or changing, tapered angle of die or shrink fitting ratio ware most interesting for further study.

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